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### New casing and backfill design for neutron logging access boreholes.
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**Abstract:** A combination of polyurethane foam backfill and acrylic casing has been developed to improve the effectiveness of neutron logging for environmental applications. Laboratory and field tests have been undertaken to assess their performance in comparison with traditional well completion components. The findings showed the effectiveness and applicability of acrylic casing and polyurethane foam backfill in the construction of neutron probe access boreholes.

Introduction

Neutron logging has found extensive application in a number of earth science-related fields. It is a technique that takes advantage of the properties of the hydrogen atom in thermalizing high energy neutrons (Gardner 1986). When high energy ([greater than]2 MeV) neutrons are emitted into a formation, they collide with other nuclei and lose energy, or become thermalized. A detector sensitive only to low energy ([less than]0.03 MeV) neutrons is used to detect the thermal neutron flux. Of all common nuclei present in earth materials, hydrogen is the most effective neutron moderator because its mass is nearly equal to that of a neutron. In soil and rock environments that do not contain hydrocarbons, water is by far the largest reservoir of hydrogen in soil or rock, making neutron attenuation particularly useful for moisture detection. In the oil industry, neutron logging has been used for decades for porosity measurement (assuming full saturation of pores), detection of gas, and general lithologic determination (Rider 1986). In agricultural sciences, the neutron probe has been used to easily and quickly monitor soil moisture content for the purpose of irrigation management (van Bavel 1963). In soil science, similar probes are used to determine changes in moisture content and to estimate infiltration and evaporation rates (Hillel 1980). Given that neutron thermalization is affected by soil density, composition, and water content, the thermal neutron flux can be interpreted semi-quantitatively at best, unless calibration to the given medium is performed (Elder and Rasmussen 1994; Ruprecht and Schofield 1990; Greacen and Schralle 1976).

It has long been recognized that the nature of the access borehole can significantly affect neutron thermalization (Amoozegar et al. 1989). Under ideal conditions, a neutron access borehole would consist of a thin-walled aluminum pipe, with an inside diameter just slightly larger than the logging tool, tightly pressed into the soil or

sediment (i.e., without backfill) (Gardner 1986). Unfortunately, such installation is not possible under most conditions. If sediments are even partly consolidated, a tight fit between the casing and the formation cannot be assured, creating the potential for annular water flow. Therefore, installations in rock or at any contaminated site generally require over-drilling and backfilling. Thin-walled aluminum pipe has a tendency to buckle, deform, and corrode. PVC casing, which is most often used in environmental applications, is not well suited for neutron logging because of its high chlorine content. Chlorine has a very large capture cross section for thermal neutrons (Celata et al. 1996) and greatly reduces the thermal neutron count, thereby reducing sensitivity. Steel casing has much less effect on neutron flux, but it is more expensive and heavy, and it interferes with most geophysical characterization methods, such as electrical resistivity or radar surveys.

The most commonly used materials for backfilling neutron access boreholes are bentonire clay, cement, and sand. All three have drawbacks. Bentonite clay is used because it is an effective sealant, due to its swelling nature. This means that, once saturated, it has a high moisture content and, being the closest material to the neutron source, it will cause the thermalization of a large fraction of the high-energy neutron flux. Furthermore, changes in formation moisture content will generally not be reflected in the moisture content of the bentonite clay, due to its strong retention of water. Cement grout has the advantage of having a more or less constant moisture content with time, but a high moisture content nonetheless. Even when applied in a well-mixed slurry, cement grout has a tendency to settle, resulting in a vertically uneven moisture distribution. A porous material chosen to resemble the formation in its moisture characteristic is, in theory, a better option for logging, but it is ineffective in sealing the borehole. Also, except in unusually homogeneous formations, it is difficult to match the composition of backfill and formation at all depths.

All these backfill scenarios result in significant attenuation of the neutron flux before it enters the formation. Most environmental applications of neutron logging use low-flux neutron sources in order to minimize worker exposure to radiation and to lower operation costs. The most commonly used neutron probes contain 50 mCi sources, with an effective radius on the order of 15 cm (Klenke and Flint 1991). A common well construction method would result in a 5 cm diameter casing inside a 15 cm diameter borehole, resulting in a 5 cm thick, backfilled annulus. Clearly, this will have a profound effect on neutron flux, especially if the backfill material is bentonite or cement grout. This problem may be resolved by either minimizing the backfilled annulus, or identifying alternative casing and backfill materials.

The purpose of this paper is to develop a combination of casing and backfill material which will enhance the ability to measure small changes in moisture content using neutron logging. Acrylic casing and polyurethane foam backfill were investigated as potential candidates for such materials. Laboratory tests were conducted to evaluate their performance in comparison with conventional well completion components.

Materials and Methods

Neutron Probe

Neutron counts were obtained using a CPN 503DR Hydroprobe (Campbell Pacific Nuclear, Martinez, California). The probe contains an 241Am-Be source producing a flux of 110,000 4.5 MeV neutrons [s.sup.-1], and a 3He thermal neutron detector. The probe has a diameter of 4.5 cm and a length of 35 cm.

Laboratory Test Design

Acrylic was considered to be a promising material for neutron access pipe because, unlike PVC, it does not contain chlorine and yet is fairly inexpensive and commonly available. The acrylic pipe used in these experiments had an I.D. of 5 cm and a wall thickness of 3.5 mm. The PVC pipe used for comparison also had an I.D. of 5 cm, but a wall thickness of 4.5 mm. 40 cm sections of acrylic and PVC pipe were cut and sealed on the bottom end with an acrylic bottom, attached with epoxy.

In order to test the effects of backfill on neutron flux, several model wells were constructed using 10 cm diameter acrylic pipe as a borehole wall and either 5 cm diameter PVC or acrylic pipe as casing. The annulus between casing and borehole wall was either left empty (i.e., air-filled) or filled with bentonite or polyurethane foam [ILLUSTRATION FOR FIGURE 1 OMITTED]. Bentonite clay backfill was made from 1 cm pellets, saturated with distilled water.

After comparing a number of different polyurethane resins, as well as colloidal silica, the polyurethane resin used to make the foam backfill was selected based on its low density, low cost, and commercial availability. The selected compound (ST530, Strata Tech Inc., Richardson, Texas; exact composition proprietary) is similar to other polyurethane resins sold at hardware stores for the purpose of filling cracks in concrete. The foam is made by mixing a urethane prepolymer resin with water and a catalyst ("accelerator") which controls the set time. The longer the set time, the lower the final bulk density of the foam. In this experiment, the final bulk density of the polyurethane foam was 0.080 g [cm.sup.-3], as compared with the density of the unreacted resin, of 1.1 g [cm.sup.-3], indicating a greater than tenfold increase in volume. Set times were approximately one minute. The resultant closed-cell foam is inert, hydrophobic, and insoluble in water. It adheres strongly to both dry and wetted soils, sediments, and rocks.

All materials were tested in air, water, and sand at various moisture contents. In order to eliminate the effects of nearby objects, the experiments were performed in the middle of a large room, and were elevated at least 30 cm from the floor. Preliminary tests were performed in air and water to assure that the readings were unaffected by surroundings. Subsequent tests were performed in a 208 L PVC dram, with a diameter of 55 cm. At first, the casing/backfill combinations were tested in air, i.e., in an empty drum, elevated

from the bottom of the drum by a glass stand. The neutron probe was placed in each casing/backfill configuration and five 16-second counts were recorded. In the next experiment, the drum was filled with water and the same procedure was repeated. Finally, the drum was filled with medium-grained silica sand ([greater than]94% Si[O.sub.2]; 99.2% of grains between 0.125 and 1 mm), by allowing it to settle through the water. This prevented entrapped air and resulted in homogeneous packing. The final dry bulk density was 1.49 g [cm.sup.-3], with a porosity of 44%. An aluminum cylinder, with an I.D. of 12 cm was buried in the middle of the drum as an access hole for the model boreholes. Water was drained through an opening at the bottom of the dram. The first readings were taken when the water level was at the surface of the sand. Samples of sediment were obtained using a coring tool with an I.D. of 2 cm. Cores 10 cm long were taken from a depth corresponding to 5 cm below and 5 cm above the location of the neutron source. These samples were oven-dried to determine moisture content (Gardner 1986). Gradually, water was partially drained from the sand, the system was allowed to equilibrate (as determined using a tensiometer), and another set of readings was taken. This was repeated until water was no longer draining out of the sand.

Field Testing

The new design was used as part of the instrumentation of the Box Canyon experimental field site near Arco, Idaho (Knutson et al. 1993). At this site, a ponded infiltration test was conducted in August and September 1996 to characterize the flow of water through a complex network of variable-thickness fractures in an unsaturated, fractured basalt formation (Faybishenko et al. 1997). Neutron logging was used alongside tensiometers, lysimeters, resistivity probes, time-domain reflectometry, and radar measurements to track the progress of water through the formation. Seven neutron probe access boreholes were installed using the materials described, including three 15 cm diameter vertical boreholes and four 10 cm diameter slanted boreholes, ranging in inclination from 27 degrees to 41 degrees from vertical. Prior to completion, all of the boreholes were logged using a downhole camera. The slanted boreholes were cased with 5 cm diameter acrylic pipe, and the vertical boreholes were cased with 7.5 cm diameter acrylic pipe, both with a wall thickness of 3.5 mm, and both of which were custom-threaded by McCabe Bros. Inc. In slanted boreholes, PVC centralizers were used approximately every 8 m; centralizers were not necessary in vertical boreholes. The pipes, which were sealed on the bottom with a glued piece of acrylic, were grouted in with polyurethane foam. Grouting, which was also performed by McCabe Bros. Inc., was accomplished by placing two grout injection tubes near the bottom of the annular space and injecting enough grout to fill 2 m of annular space. The final bulk density of the injected foam was 0.13 g [cm.sup.-3]. After five minutes the grouting tubes were pulled to the next level to be grouted, and the process was repeated. No problems were encountered in cutting, threading, or installation of acrylic pipe. Each borehole was logged before the infiltration test and once or twice daily for a period of approximately 10 days after the initiation of ponding. The same access holes were used for radar imaging before, during, and after the test. Despite repeated insertion of the neutron probe and radar transmitters and receivers through acrylic pipes, which extended up to 1

m above ground surface, no damage to the casings was observed.

Results

Laboratory Testing

Throughout this experiment, the statistical error of the neutron counts (five measurements for each data point) was small, with a coefficient of variance consistently below 3%. These errors are generally not visible on the scale shown in Figures 2 through 5. Data is shown in actual neutron counts, not normalized to "blank" readings, as it is often presented (e.g., Evett and Steiner 1995), so that a better appreciation can be gained of the count resolution under various conditions.

Thermal neutron counts obtained in air and varying annuli of water through acrylic and PVC casings are shown in Figure 2. It is apparent that under all conditions the thermal neutron count taken through the acrylic casing is the same as one taken with no casing at all, while the thermal neutron flux is strongly attenuated by the PVC casing. Also, it appears that all fast neutrons are thermalized within approximately 12 cm of the probe. based on these findings, acrylic was used to construct "boreholes," as shown in Figure 1, and a 55 cm diameter drum was considered to be of adequate size for subsequent experiments.

The results of neutron logging in air and water through the model borehole and casings with and without backfill are shown in Figure 3. The decrease in the absolute readings from Figure 2 to Figure 3 is the result of the presence of a 2.5 cm thick air gap between the neutron probe and the sand, an effect that has been previously described (Tyler 1988; Amoozegar et al. 1989). As expected, the results obtained with acrylic casing were almost the same as those taken without a casing, while PVC casing caused attenuation. The addition of polyurethane foam backfill to the borehole containing acrylic casing caused only a slight increase in thermal neutron flux, likely the result of thermalization of neutrons by H in the polyurethane. Addition of bentonite backfill to the PVC-cased borehole caused an increase in thermal neutron counts, due to the high H content in the water-saturated bentonite. The presence of PVC and bentonite resulted in a 43% loss in neutron count range (i.e., loss of sensitivity) by reducing the slope of the count ratio vs. moisture content relationship.

Thermal neutron fluxes measured in variably saturated sand, using acrylic- and PVC-cased model boreholes, are presented in Figures 4 and 5, respectively. Once more, a similar effect is observed, in which neutron counts collected through the acrylic/polyurethane model borehole are almost identical to the no casing (empty borehole) scenario. Also, the poor sensitivity of the combination of PVC and bentonite is underscored, as the slope is further decreased in the dry range due to the presence of water in the bentonite. None of the curves in Figure 4 exhibit consistently linear trends, but rather there is a change in slope in the data at a volumetric moisture content of around 0.14. This also corresponds to a time when the water table, which was being

lowered inside the drum, was just below the bottom of the neutron probe unit. Because of the low moisture retention of the medium sand used in this experiment, readings corresponding to intermediate volumetric moisture contents were taken while the water table was not completely below the depth of the source. As a result, the measured neutron flux was integrated over both saturated and unsaturated intervals within the sand. This points out potential problems with the quantitative use of neutron logging near a saturated-unsaturated boundary, such as a water table, perched water, or an infiltrating front, even if precise calibration is available.

Field Testing

Data from the field experiment indicated that the new borehole design was well suited to monitoring water flow in fractured basalt. Logs from the borehole camera revealed a complex system of fractures, vesicular basalt, and rubble zones (Faybishenko et al. 1998). By using the neutron logs, it was possible to observe increases in moisture content in and around features identified in camera logs. An example of the logging results from one of the slanted boreholes (R-3; 27.3 degrees from vertical) is shown in Figure 6. The readings have been normalized to the initial, pre-ponding reading, which then assumes the value of one along the entire depth of the borehole. Increases in moisture content were observed either shortly after ponding, such as at the depth of 4 m, indicating a strong and direct connection of the fracture to water-conducting features near the surface; more gradually, such as at the depth of 8 m, indicating a more complicated connection; or not at all, such as at depths of 2.2 m, where a fracture exists but is apparently not connected to the water-bearing features. Data collected one year later show decreases in moisture in major features but no significant redistribution of moisture to drier regions, confirming the integrity of the polyurethane backfill. The only notable exception is an increase in moisture within the top 1 m of the formation, an observation confirmed by data from other boreholes, and explained by the overall wetter field conditions in 1997, following a wet winter.

Discussion

The results presented herein demonstrate the usefulness and applicability of acrylic casing and polyurethane foam backfill in the construction of neutron probe access boreholes. Due to its limited attenuation of neutrons, polyurethane foam can be used effectively in sealing annuli of boreholes without compromising logging results. This could be particularly useful for installation in oversized boreholes in unstable geologic media. Acrylic pipe does not significantly reduce the thermal neutron flux via absorption. Although threaded acrylic well pipe is not commercially available, acrylic pipe can be custom-threaded at reasonable cost. Polyurethane foam is especially well suited for backfilling boreholes in fractured rock because of its fast set time, which minimizes penetration into fractures. This design allowed for the tracking of water flow through fractured basalt with fairly high resolution and complimentary radar imaging through the same access boreholes.

The field test provided evidence that the new borehole design meets several criteria. The installation in fractured basalt, both in vertical and slanted boreholes, was rapid and without complication. Because the resin expands in situ, the total bulk and mass of material is far smaller than with, for example, bentonite. Its injection into the borehole can be carefully controlled. Both the unprotected acrylic casing and polyurethane foam, which have been exposed to two years of extreme temperature and moisture conditions at the surface of the site, have shown no signs of damage or decomposition.

Additional work is required to test other possibilities for using this method. Installation below the water table should be possible, especially since water is used in the activation of the resin, and the foam is hydrophobic. Although similar resin compositions have been used to fill fractures in dams (Smoak 1991), the maximum pressure under which the resin can be injected needs to be determined. Further work is needed to define the optimal polyurethane resin composition for this application and measure the hydraulic properties of the final foam product. Finally, long-term stability of this product, especially when used at contaminated sites, needs to be addressed.

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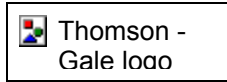Rider, M.H. 1986. The Geological Interpretation of Well Logs. New York: Halsted Press.

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